Roles of tensor and pairing correlations in neutron drip-line nuclei

Takayuki MYO　明 孝之
Osaka Institute of Technology
大阪工業大学

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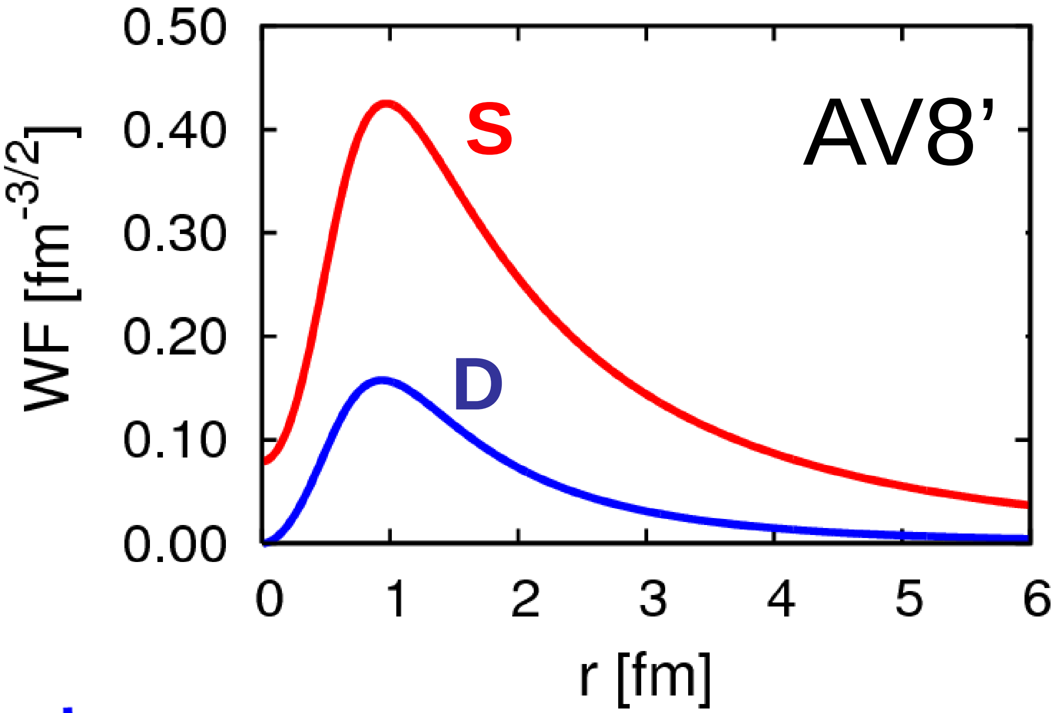
Purpose & Outline

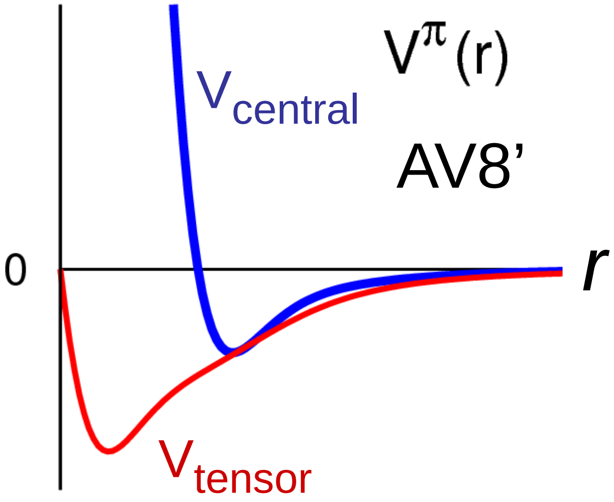
- **Role of V_{tensor}** in the nuclear structure by describing strong tensor correlation explicitly.
- Tensor Optimized Shell Model (TOSM) to describe tensor correlation.
- Unitary Correlation Operator Method (UCOM) to describe short-range correlation.
- TOSM+UCOM to He & Li isotopes with V_{bare}
- Halo formation in ^{11}Li
  - Coexistence of tensor and pairing correlations

TM, A. Umeya, H. Toki, K. Ikeda, PRC84 (2011) 034315.

Deuteron properties & tensor force



Energy	-2.24 MeV
Kinetic	19.88
Central	-4.46
Tensor	**-16.64**
LS	-1.02
P($L=2$)	5.77%
Radius	1.96 fm



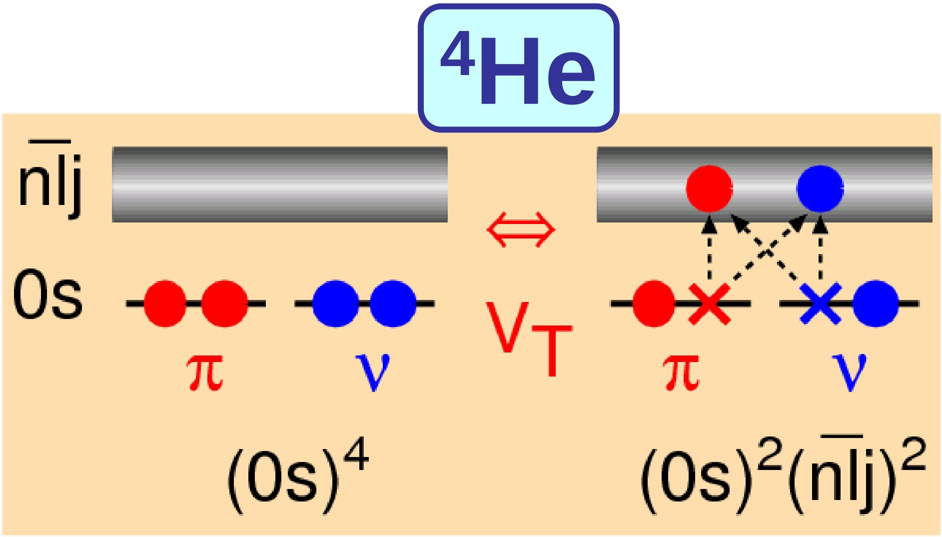
$R_m(s)=2.00$ fm

$R_m(d)=1.22$ fm

d-wave is
“**spatially compact**”
(high momentum)

Tensor-optimized shell model (TOSM)

TM, Sugimoto, Kato, Toki, Ikeda PTP117(2007)257



- Configuration mixing within 2p2h excitations with high-L orbits.

  TM et al., PTP113(2005)
  TM et al., PTP117(2007)
  T.Terasawa, PTP22('59))

- Length parameters such as b_{0s}, b_{0p}, … are optimized independently (or superposed by many Gaussian bases).
  - Describe high momentum component from V_{tensor}
  - Spatial shrinkage of relative ***D*-wave** component as seen in deuteron

    HF by Sugimoto et al,(NPA740) / Akaishi (NPA738)
    RMF by Ogawa et al.(PRC73), AMD by Dote et al.(PTP115)

Hamiltonian and variational equations in TOSM

$$H = \sum_{i=1}^{A} t_i - T_G + \sum_{i<j}^{A} v_{ij},$$

(0p0h+1p1h+2p2h)

$$\Phi = \sum_k C_k \cdot \psi_k$$

ψ_k : shell model type configuration

Particle state : Gaussian expansion for each orbit

$$\varphi_{lj}(\mathbf{r}) = \sum_{n=1}^{N} C_{lj,n} \cdot \phi_{lj,n}(\mathbf{r})$$

$$\phi_{lj,n}(\mathbf{r}) = N_l(b_n) \cdot r^l e^{-\left(r/b_n\right)^2} \left[Y_l(\hat{\mathbf{r}}), \chi^{\sigma}_{1/2}\right]_j \chi^{\tau}_{t_z}$$

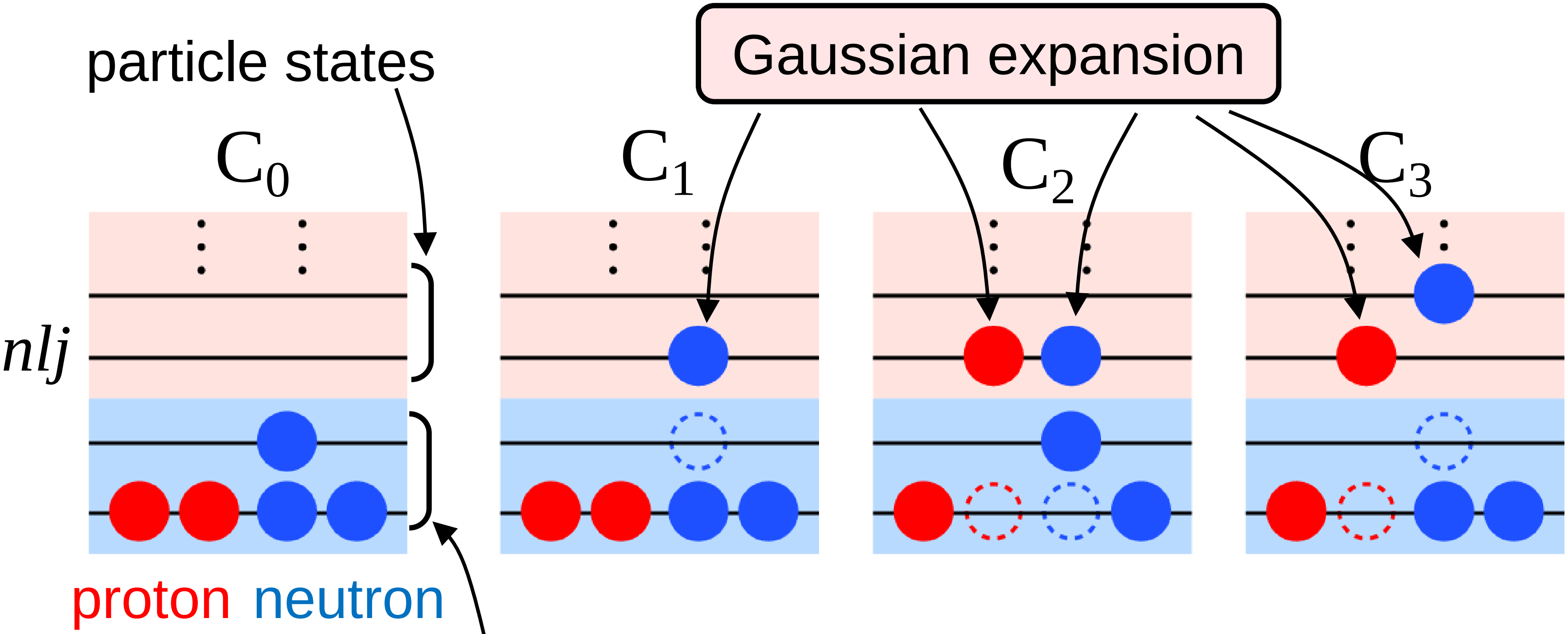
Gaussian basis function

$$\frac{\partial \langle H - E \rangle}{\partial C_k} = 0, \qquad \frac{\partial \langle H - E \rangle}{\partial C_{lj}} = 0, \qquad \frac{\partial \langle H - E \rangle}{\partial b_n} = 0$$

TOSM code : *p*-shell region

c.m. excitation is excluded by Lawson's method

Configurations in TOSM



hole states
(harmonic oscillator basis)

Application to Hypernuclei by Umeya
(ΛN-ΣN coupling)

c.m. excitation is excluded by Lawson's method

Unitary Correlation Operator Method

(short-range part)

$$\Psi_{\text{corr.}} = C \cdot \Phi_{\text{uncorr.}}$$

TOSM

short-range correlator

$C^{\dagger 1} = C^{-}$ (Unitary trans.)

$$H\Psi = E\Psi \;\rightarrow\; C^{\dagger} H C \Phi \equiv \widehat{H}\Phi = E\Phi$$

Bare Hamiltonian

Shift operator depending on the relative distance

$$C = \exp\Big(-i\sum_{i<j} g_{ij}\Big), \qquad g_{ij} = \tfrac{1}{2}\left\{ p_r \underline{s(r_{ij})} + \underline{s(r_{ij})}\, p_r \right\} \qquad \vec{p} = \vec{p}_r + \vec{p}_\Omega$$

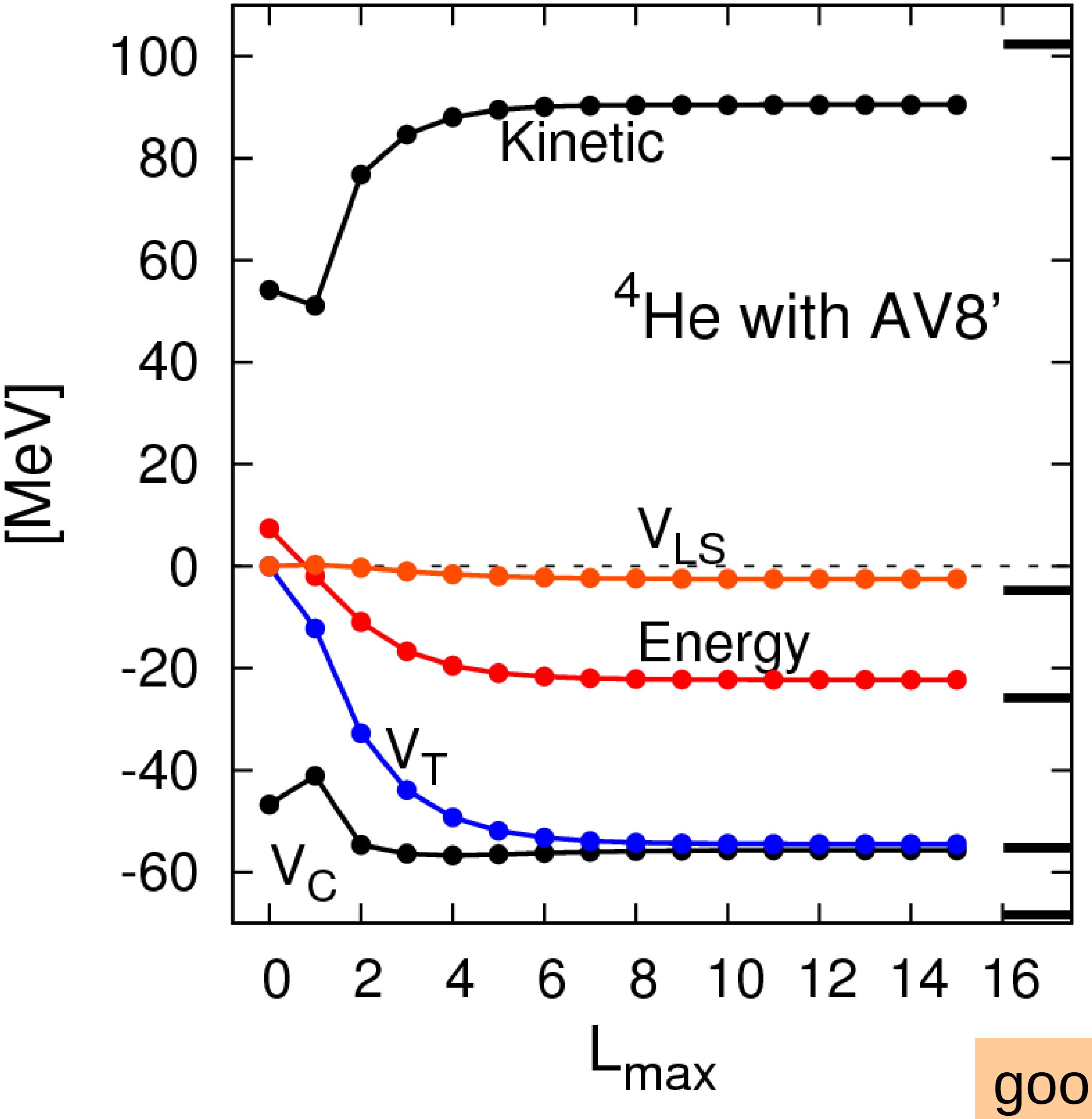
Amount of shift, variationally determined.

$$C^{\dagger} r C \simeq r + s(r) + \tfrac{1}{2} s(r) s'(r) \cdots$$

2-body cluster expansion

H. Feldmeier, T. Neff, R. Roth, J. Schnack, NPA632(1998)61

^{4}He in TOSM + *S*-wave UCOM



T (exact)

Kamada et al.
PRC64 (Jacobi)

TM, H. Toki, K. Ikeda
PTP121(2009)511

V_{LS}

E

V_C

V_T

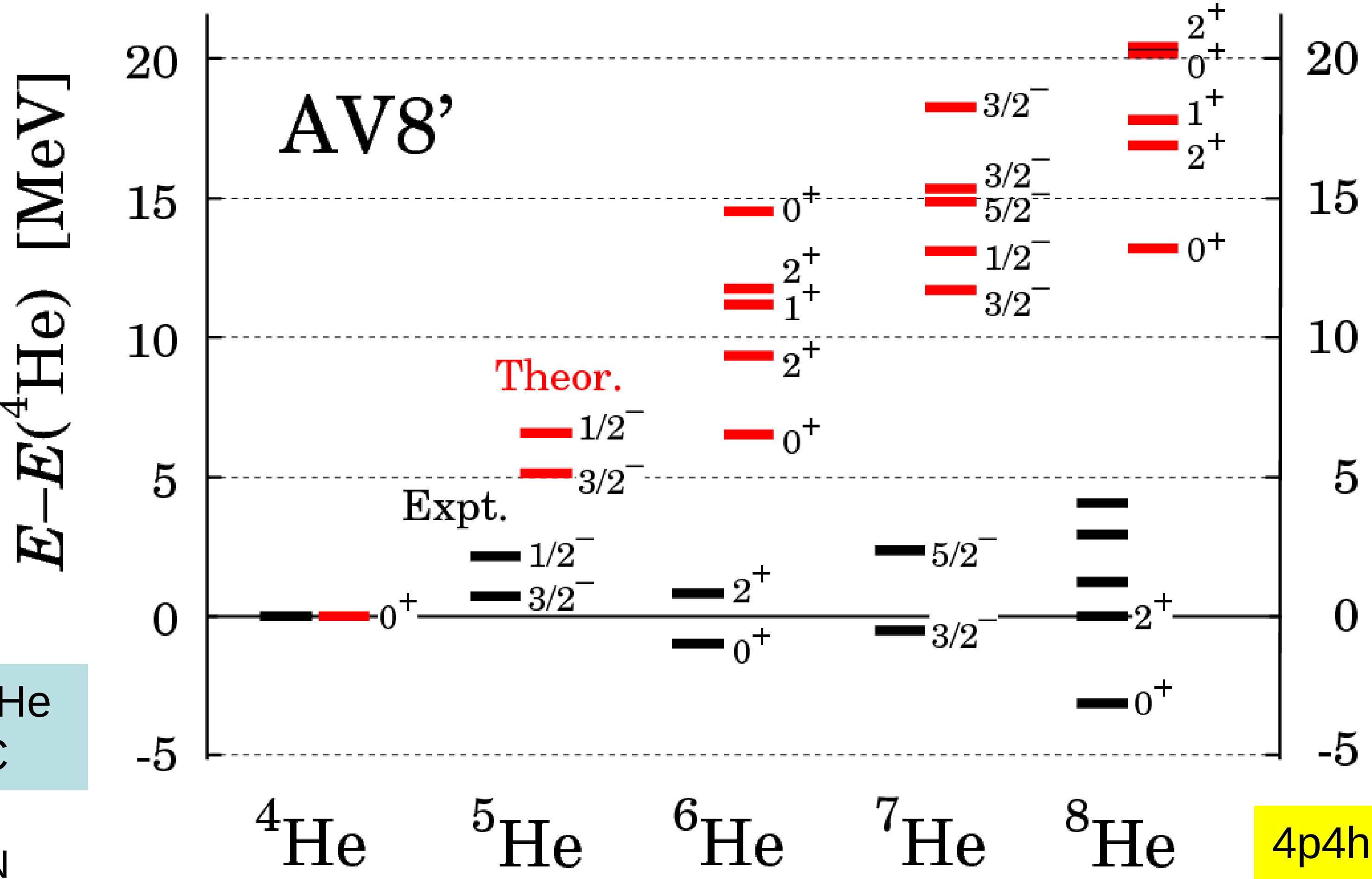
- variational calculation

- Gaussian expansion with 9 Gaussians

good convergence

$^{4-8}$He with TOSM+UCOM

- Difference from ^{4}He in MeV



~6 MeV in ^{8}He using GFMC

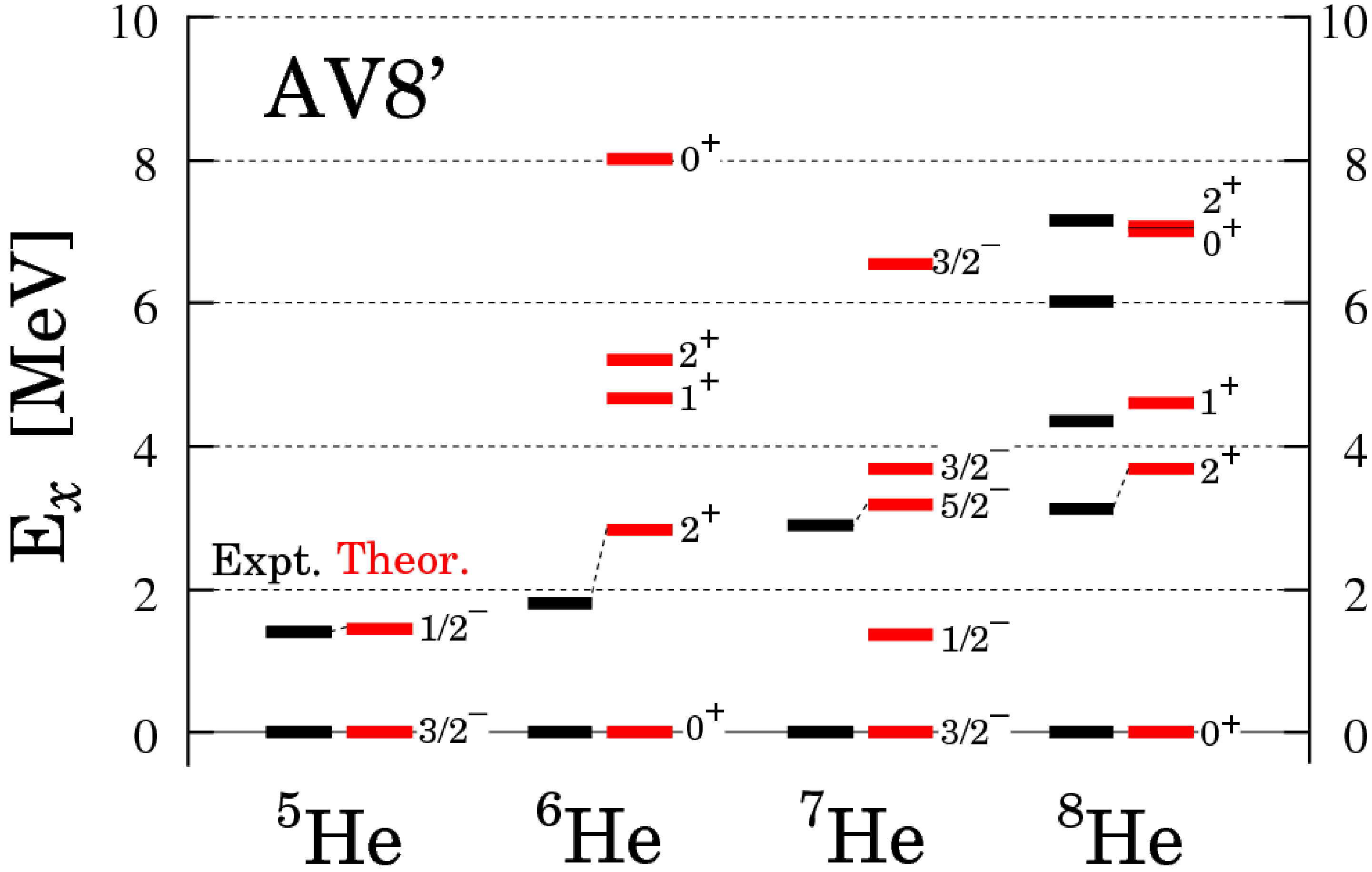
- No V_{NNN}
- No continuum

4p4h in TOSM

~7 MeV in ^{8}He using Cluster model (PLB691(2010)150 , TM et al.)

$^{4\text{-}8}$He with TOSM+UCOM

- Excitation energies in MeV

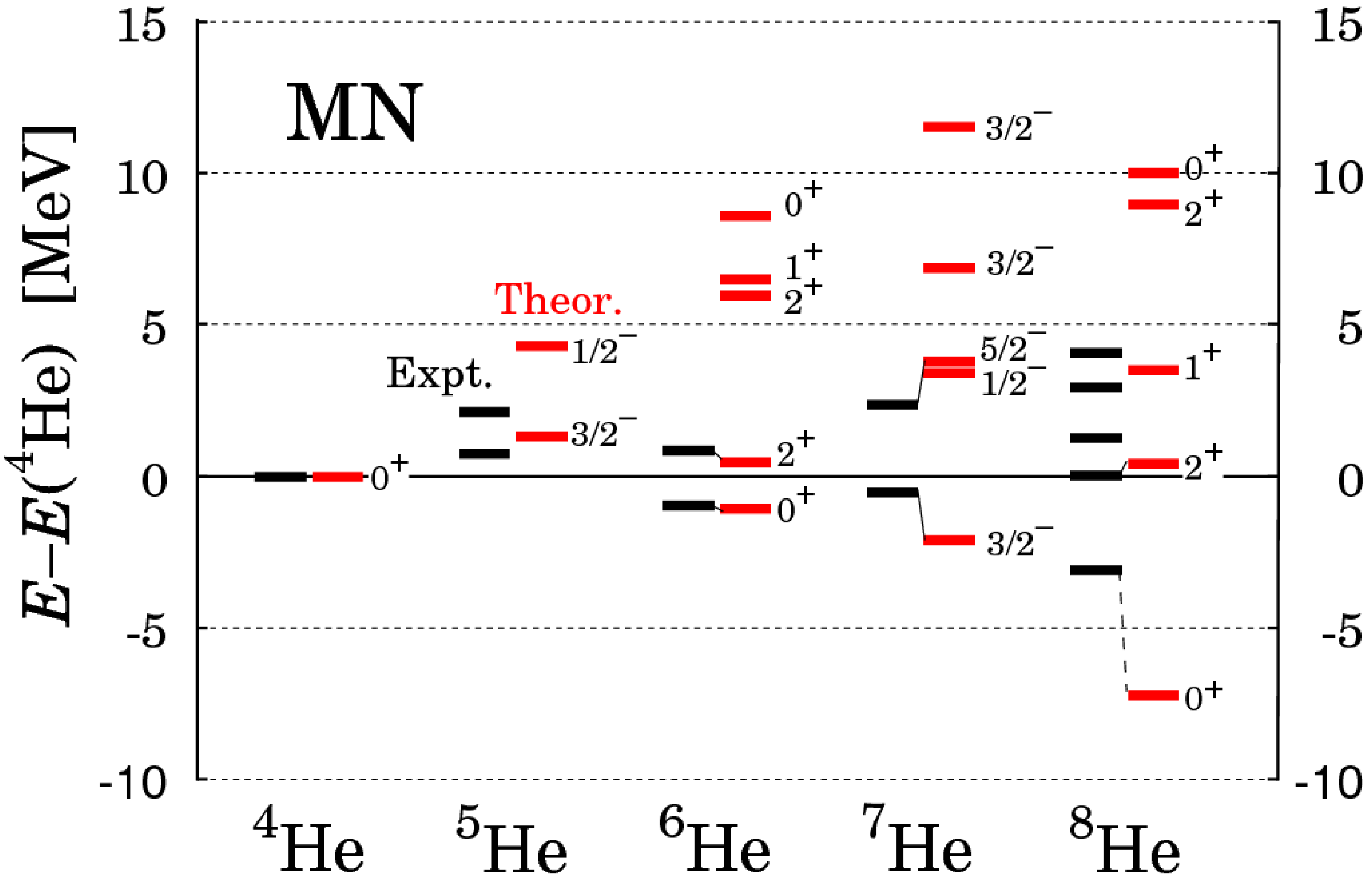


- No V_{NNN}
- No continuum
- Excitation energy spectra are reproduced well

$^{4\text{-}8}$He with TOSM

Minnesota force (Central+LS)

- Difference from ^{4}He in MeV

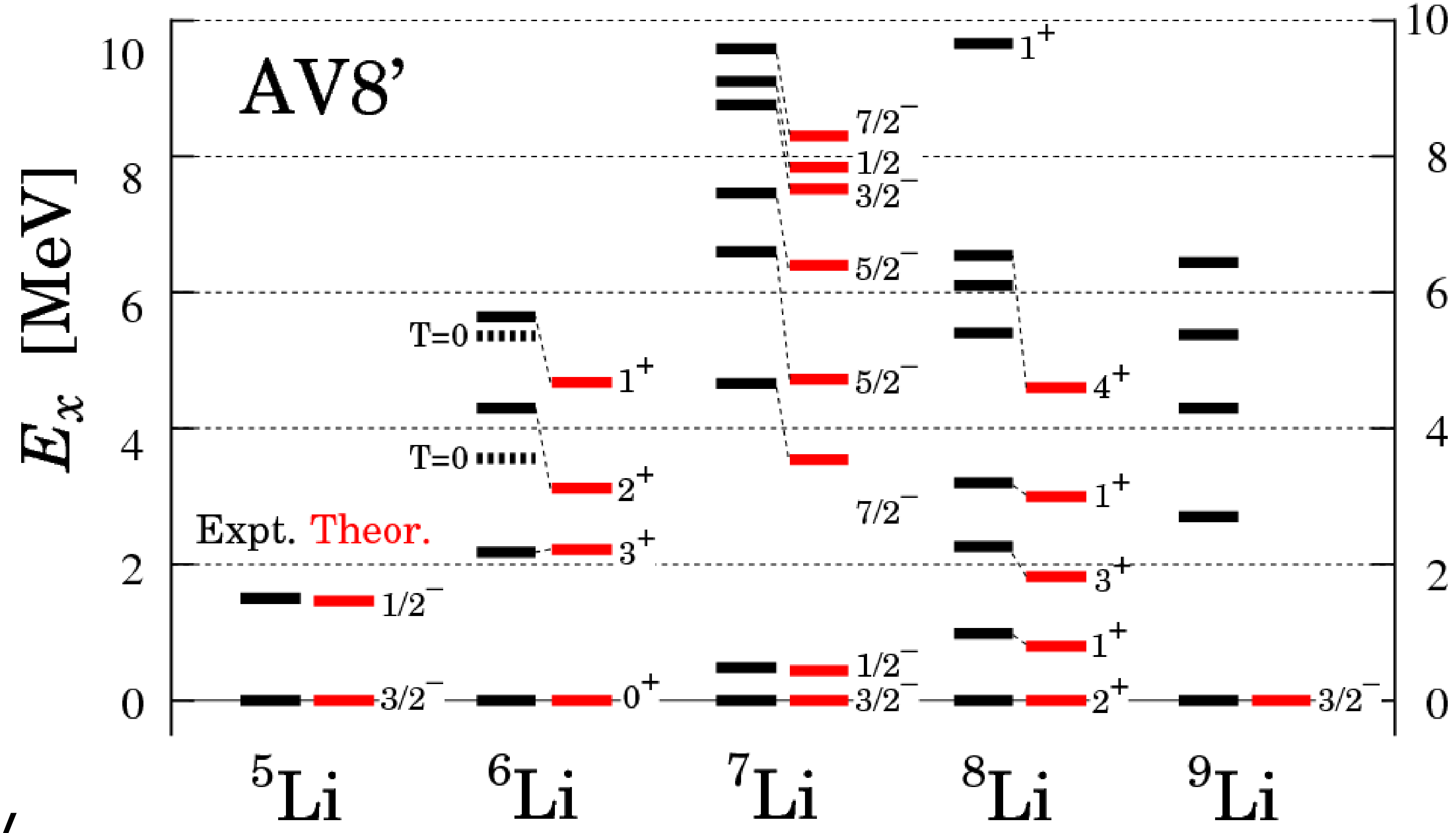


- No V_{NNN}
- No continuum

$^{5-9}$Li with TOSM+UCOM

- Excitation energies in MeV

Preliminary results



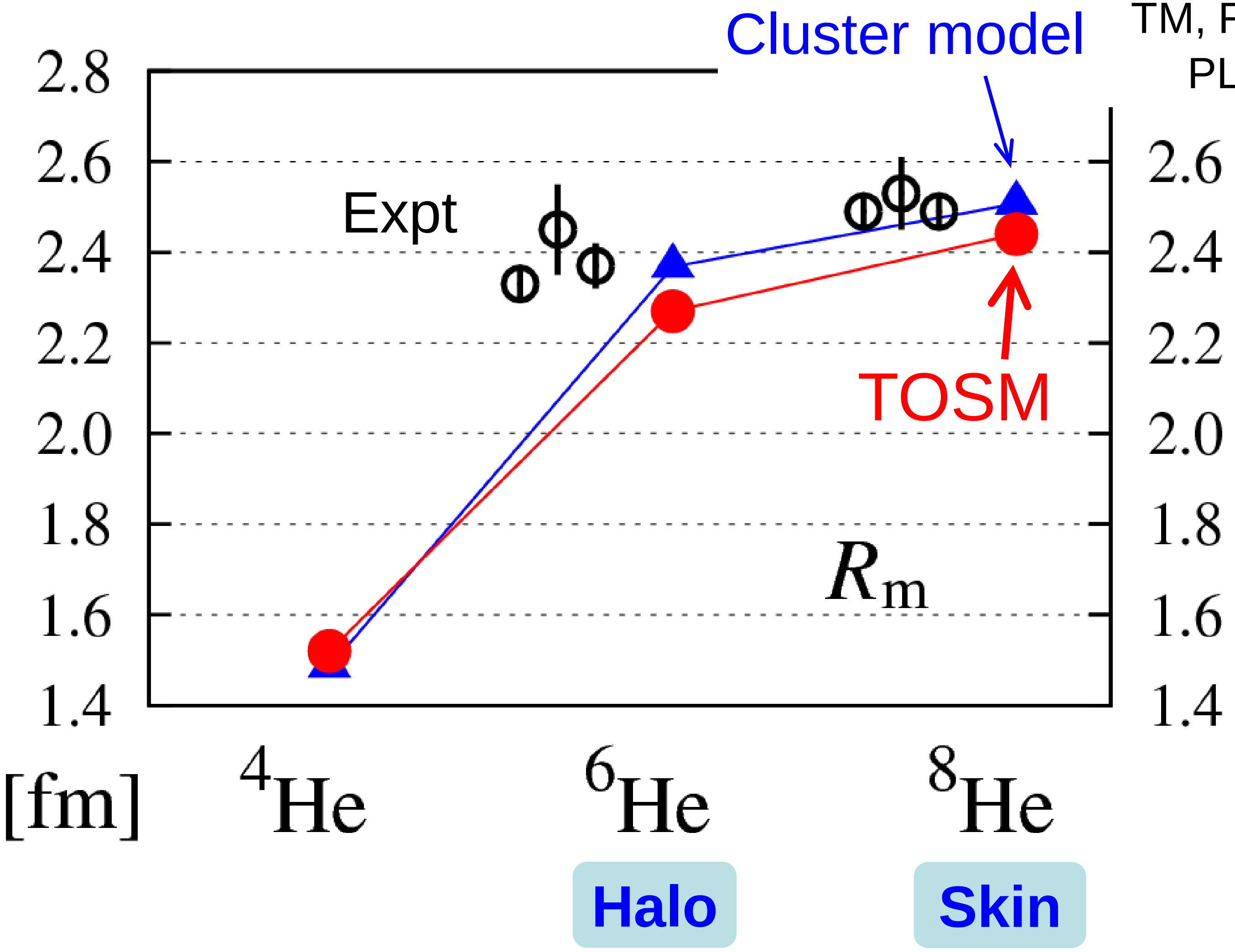
- No V_{NNN}
- No continuum

- Excitation energy spectra are reproduced well

Matter radius of He isotopes

TM, R. Ando, K. Kato
PLB691(2010)150

$^{A}\text{He} = \alpha + 4n$



I. Tanihata et al., PLB289('92)261
O. A. Kiselev et al., EPJA 25, Suppl. 1('05)215.
G. D. Alkhazov et al., PRL78('97)2313
P. Mueller et al., PRL99(2007)252501

Configurations of ^{4}He

TM, H. Toki, K. Ikeda
PTP121(2009)511

$(0s_{1/2})^4$	83.0 %
$(0s_{1/2})^{-2}_{JT}(p_{1/2})^2_{JT}$ **JT=10**	2.6
JT=01	0.1
$(0s_{1/2})^{-2}_{10}(1s_{1/2})(d_{3/2})_{10}$	2.3
$(0s_{1/2})^{-2}_{10}(p_{3/2})(f_{5/2})_{10}$	1.9
Radius [fm]	1.54

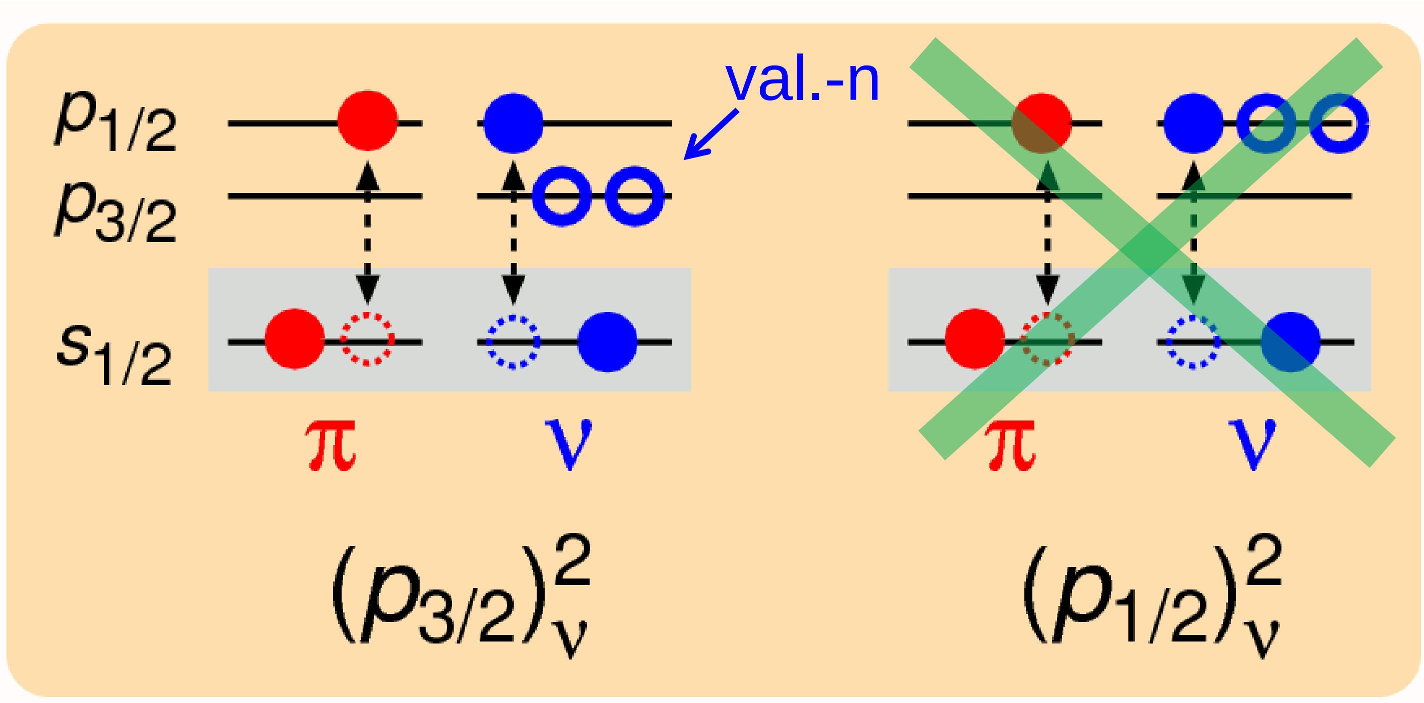
- 0^- of pion nature.
- deuteron correlation with (J,T)=(1,0)

Cf. R.Schiavilla et al. (VMC)
PRL98(2007)132501
R. Subedi et al. (JLab)
Science320(2008)1476

^{12}C(e,e'pN)

- ^{4}He contains $p_{1/2}$ of "***pn*-pair**".

Tensor correlation in ^{6}He



Ground state

halo state (0^+)

Excited state

Tensor correlation is **suppressed** due to Pauli-Blocking

TM, K. Kato, K. Ikeda, J. Phys. G31 (2005) S1681

^{6}He : Hamiltonian component

- Difference from ^{4}He in MeV

^{6}He	**0^{+}_{1}**	**2^{+}_{1}**	**0^{+}_{2}**
***n*^{2} config**	**$(p_{3/2})^2$**	**$(p_{3/2})^2$**	**$(p_{1/2})^2$**
ΔKin.	**53.0**	**52.4**	**34.3**
ΔCentral	**–27.8**	**–22.9**	**–14.1**
ΔTensor	**–12.0**	**–12.8**	**–0.2**
ΔLS	**–4.0**	**–5.0**	**2.1**

b_{hole}=1.5 fm

$\hbar\omega$=18.4 MeV (hole)

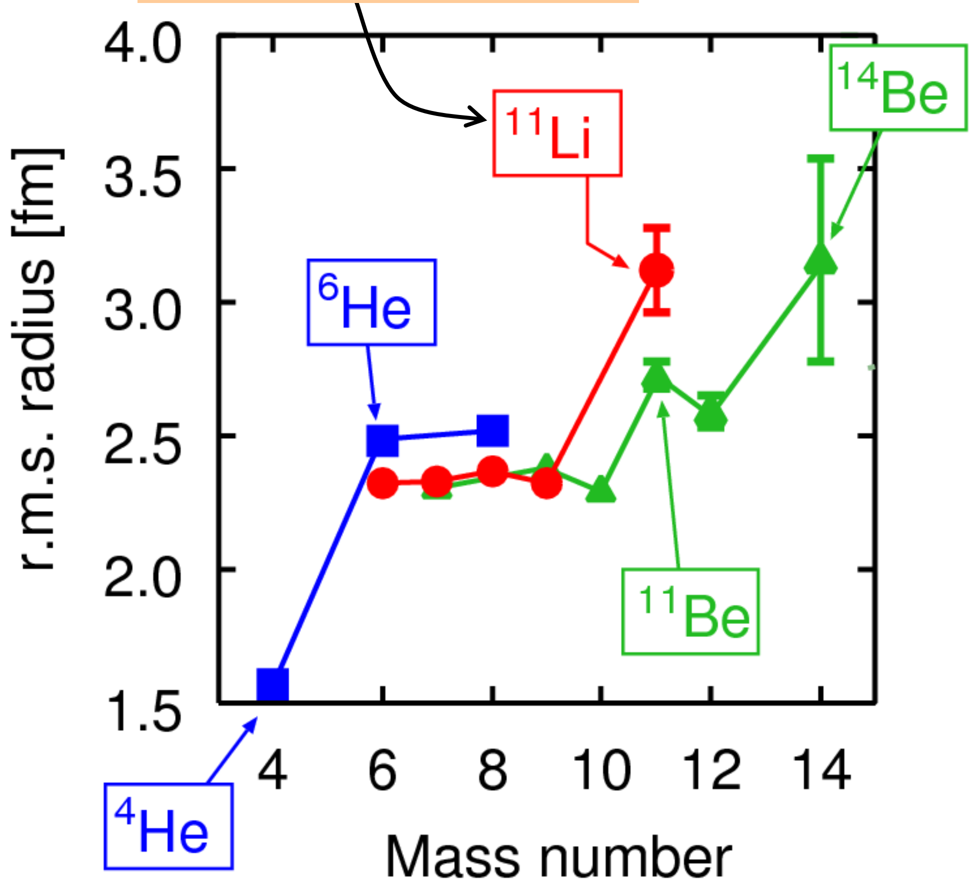
same trend in $^{5\text{-}8}$He

LS splitting energy in ^{5}He

Terasawa, Arima, PTP23 ('60)
Nagata, Sasakawa, Sawada, Tamagaki, PTP22('59)
Myo, Kato, Ikeda PTP113 ('05)

Characteristics of Li-isotopes

Halo structure

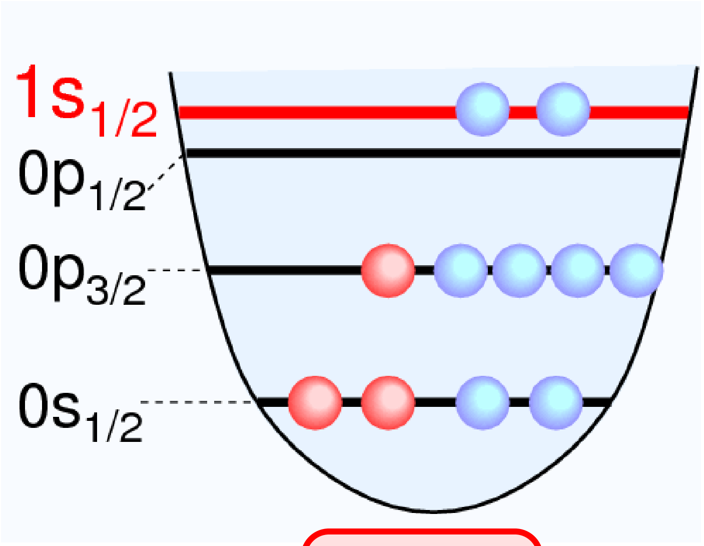


Tanihata et al., PRL55(1985)2676.
PLB206(1998)592.

✓ Breaking of magicity N=8

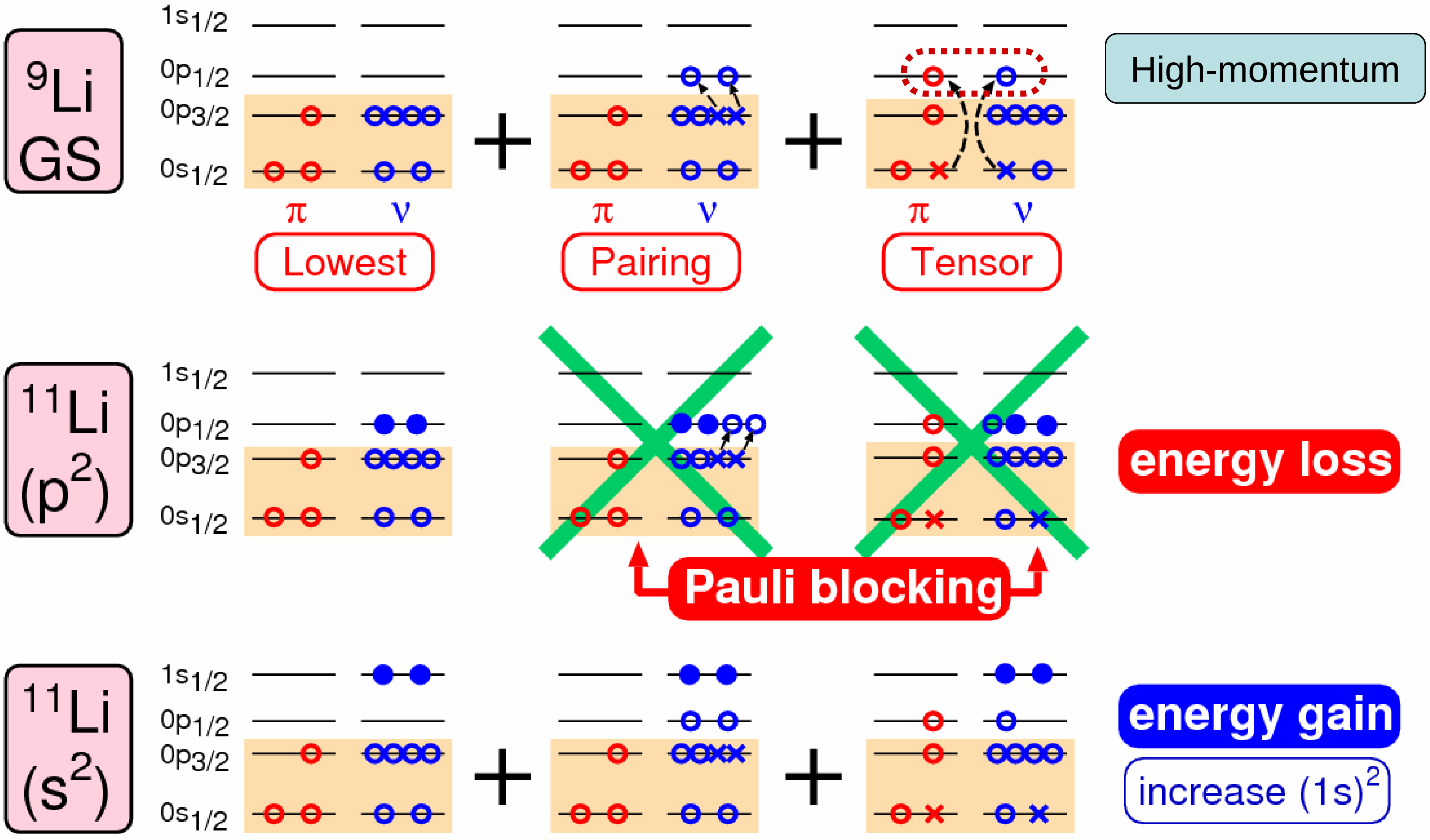
- $^{10\text{-}11}$Li, $^{11\text{-}12}$Be
- ^{11}Li … $(1s)^2$ ~ 50%.

  (Expt by Simon et al.,PRL83)
- Mechanism is unclear



^{11}Li

Expected effects of pairing and tensor correlations in ^{11}Li



Pairing-blocking :

K.Kato,T.Yamada,K.Ikeda,PTP101(‘99)119, Masui,S.Aoyama,TM,K.Kato,K.Ikeda,NPA673('00)207.
TM,S.Aoyama,K.Kato,K.Ikeda,PTP108('02)133, H.Sagawa,B.A.Brown,H.Esbensen,PLB309('93)1.

^{11}Li in coupled ^{9}Li+n+n model

- System is solved based on RGM

$$H(^{11}\mathrm{Li}) = H(^{9}\mathrm{Li}) + H_{nn} \qquad \Phi(^{11}\mathrm{Li}) = \mathcal{A}\left\{\sum_{i=1}^{N}\psi_i(^{9}\mathrm{Li})\cdot\chi_i(nn)\right\}$$

$$\sum_{i=1}^{N}\left\langle\psi_j(^{9}\mathrm{Li})\middle|H(^{11}\mathrm{Li})-E\middle|\mathcal{A}\left\{\psi_i(^{9}\mathrm{Li})\cdot\chi_i(nn)\right\}\right\rangle = 0$$

$\psi_i(^{9}\mathrm{Li})$: shell model type configuration $\rightarrow$ TOSM

- Orthogonality Condition Model (OCM) is applied.

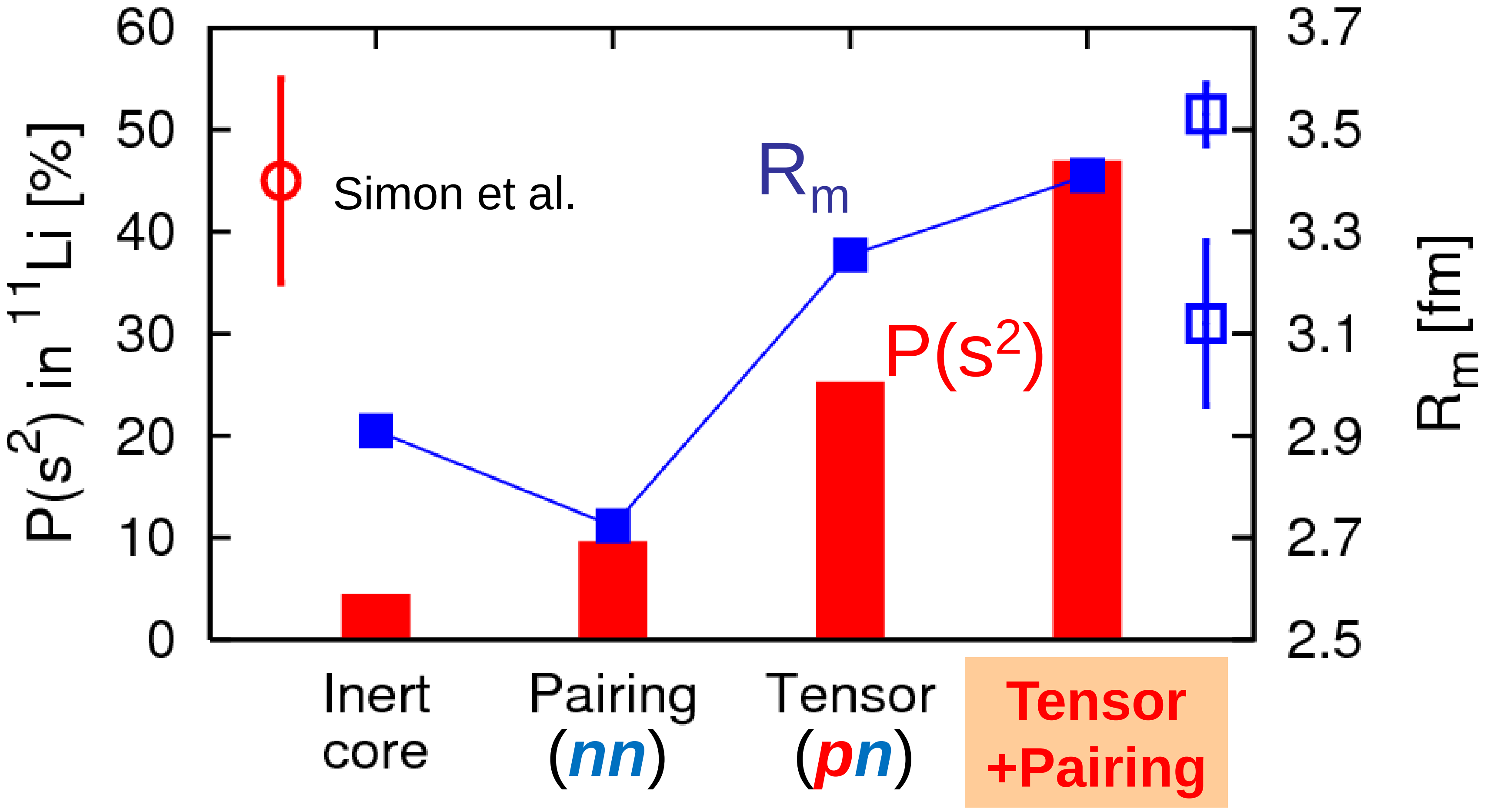
$$\sum_{i=1}^{N}\left[H_{ij}(^{9}\mathrm{Li}) + (T_1 + T_2 + V_{c1} + V_{c2} + V_{12})\cdot\delta_{ij}\right]\chi_j(nn) = E\chi_i(nn)$$

$H_{ij}(^{9}\mathrm{Li}) = \left\langle\psi_i\middle|H(^{9}\mathrm{Li})\middle|\psi_j\right\rangle$: Hamiltonian for ^{9}Li

$\chi(nn) = \mathcal{A}\{\varphi_1\varphi_2\}$: few-body method with Gaussian expansion

$\left\langle\varphi_i\middle|\phi_\alpha\right\rangle = 0,\ \{\phi_\alpha \in {}^{9}\mathrm{Li}\}$: Orthogonality to the Pauli-forbidden states

^{11}Li G.S. properties (S_{2n}=0.31 MeV)

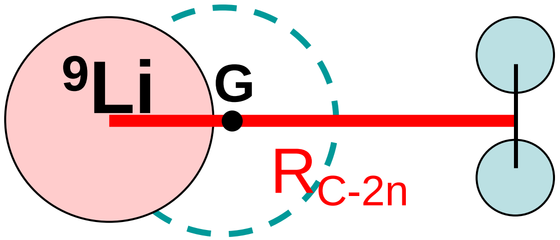


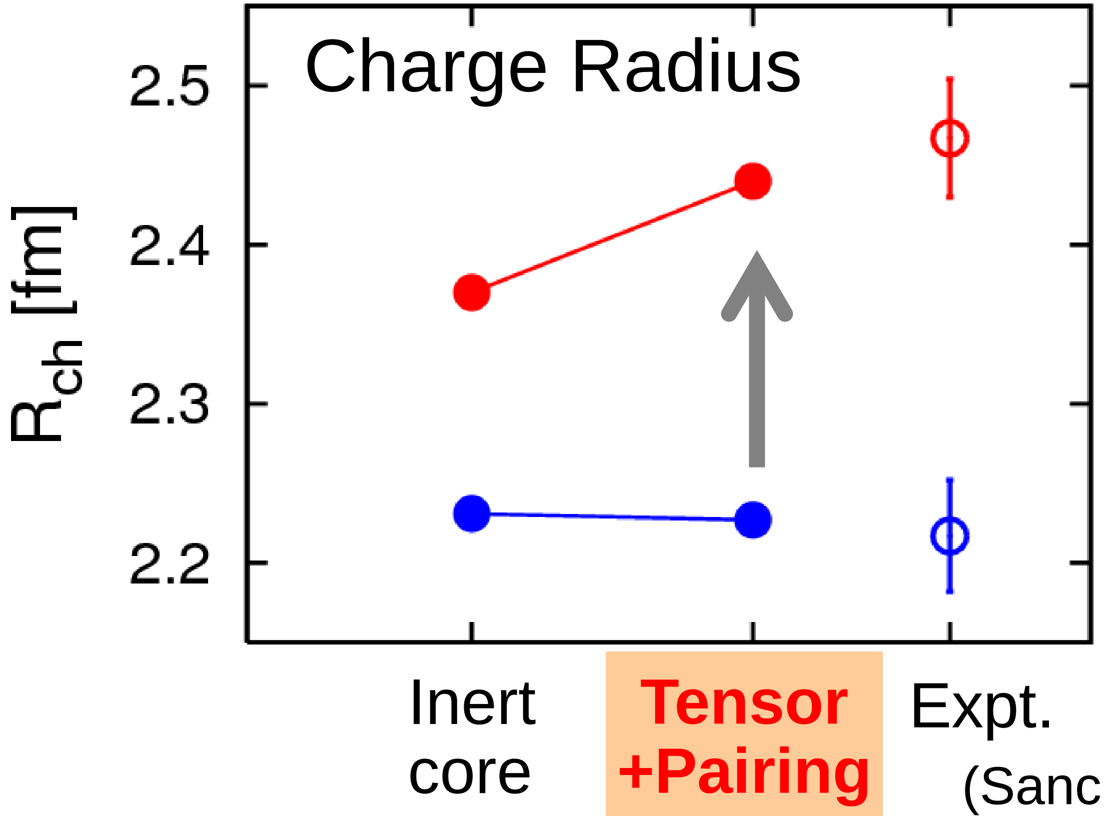
$E(s^2)-E(p^2)$	2.1	1.4	0.5	-0.1	[MeV]

Pairing correlation couples $(0p)^2$ and $(1s)^2$ for last 2n

Charge Radii of Li isotopes

$$R^2_{\text{proton}}(^{11}\text{Li}) = R^2_{\text{proton}}(^{9}\text{Li}) + \left(\frac{2}{11}\right)^2 R^2_{\text{C-2n}}$$



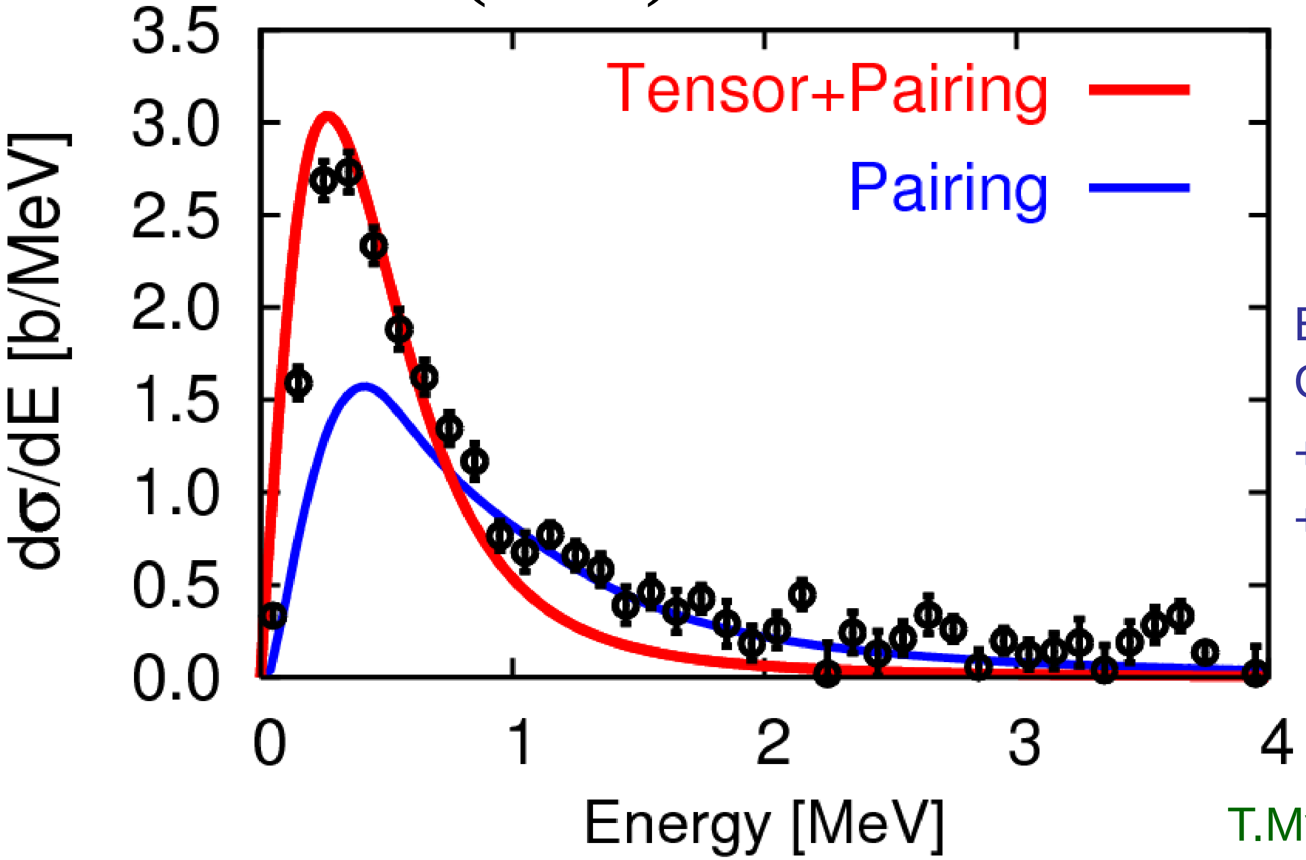


(Sanchez et al., PRL96('06))

$R_{\text{C-2n}}$	4.67	5.69	[fm]
$P(s^2)$	4	47	%

Coulomb breakup strength of ^{11}Li

$$^{11}\mathrm{Li}\,(\mathrm{G.S.}) \rightarrow\ ^{9}\mathrm{Li}+n+n$$



No three-body resonance

E1 strength by using the Green's function method

+Complex scaling method

+Equivalent photon method
(TM et al., PRC63('01))

T.Myo, K.Kato, H.Toki, K.Ikeda
PRC76(2007)024305

- Expt: T. Nakamura et al. , PRL96,252502(2006)
- Energy resolution with $\sqrt{E}$ =0.17 MeV.

Summary

- **TOSM+UCOM** with bare nuclear force.
- ^{4}He contains **"*pn*-pair of $p_{1/2}$"** than $p_{3/2}$.
- He isotopes with $p_{3/2}$ has large contributions of V_{tensor} & Kinetic energy than those with $p_{1/2}$.
  - $\boldsymbol{V}_{\textbf{tensor}}$ enhances *LS* splitting energy.
- **Halo formation in ^{11}Li** with tensor and pairing correlations.

Review **Di-neutron clustering and deuteron-like tensor correlation in nuclear structure focusing on ^{11}Li**
K. Ikeda, T. Myo, K. Kato and H. Toki
Springer, Lecture Notes in Physics 818 (2010)
"Clusters in Nuclei" Vol.1, 165-221.